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Hydrogen as an energy carrier: Prospects and challenges

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ABSTRACT

This paper provides an insight to the feasibility of adopting hydrogen as a key energy carrier and fuel source in the near future. It is shown that hydrogen has several advantages, as well as few drawbacks in using for the above purposes. The research shows that hydrogen will be a key player in storing energy that is wasted at generation stage in large-scale power grids by off-peak diversion to dummy loads. The estimations show that by the year of 2050 there will be a hydrogen demand of over 42 million metric tons or 45 billion gallon gasoline equivalent (GGE) in the United States of America alone which can fuel up 342 million light-duty vehicles for 51×10^{11} miles (82×10^{11} km) travel per year. The production at distributed level has also been discussed. The paper also presents the levels of risk in production, storage and distribution stages and proposes possible techniques to address safety issues. It is shown that the storage in small to medium scale containers is much economical compared to doing the same at large-scale containers. The study concludes that hydrogen has a promising future to be a highly feasible energy carrier and energy source itself at consumer level.

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Contents

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1. Introduction

Global warming and energy crisis are among the most important issues that threaten the peaceful existence of the man-kind. They have been showing their faces much more clearly in the past century and no concrete solution is introduced in order to curb their ill-effects on the planet. Many different approaches are under experimental investigations or being utilized in this regard. However, adopting clean and emission-free energy cycle is known to be a major break-through in this regard. The idea of using hydrogen as an energy carrier was strengthened noticeably after the global energy crisis of 1974 [1,2]. Outstanding properties and features of hydrogen make it a very promising energy carrier or fuel, although it is not naturally available as a ready to use substance.

Different methods are being used in order to mass produce hydrogen. According to its abundance, hydrogen can be extracted from a variety of materials and compounds or be produced by utilizing a wide range of methods including some clean and "green" approaches. More importantly, hydrogen can be produced anywhere across the planet. Exceptional energy per mass content, storage and transportation possibilities, safety features and reduced harmful emissions are few advantages of this substance as an energy carrier.

For many researchers that investigate the applications of hydrogen as an energy carrier or fuel require readily extractable broad-spectrum knowledge on various processes involved in this regard including their pros and cons and possible modifications that make the processes suitable for future development. Such literature is rare to be found as many research papers address narrowly focused aspects of the subject.

In this paper, we analyze almost all methods of hydrogen mass-production and distribution. Moreover, the possibilities of storing energy in small and large scales are also being reviewed. Our main emphasis is on the possibilities of storing the surplus energy production of power plants, the available off-peak grid power for such production and the energy produced from renewable sources in the form of hydrogen.

2. Information and data

2.1. Properties of hydrogen as a fuel

Hydrogen is the most abundant and simple substance of the universe [3,4]. It is a colorless, odorless and tasteless element [4,5]. Unlike conventional petroleum-based fuels and natural gas derivatives, it has a very small and light molecular structure. Some of the properties of a hydrogen molecule are summarized in Table 1 [6–9].

The nucleus of hydrogen consists of one proton and one electron. Neutron bombardment of hydrogen-containing compounds may lead to the formation of hydrogen isotopes [10], H^2 and H^3 which are called deuterium and tritium relatively [11]. Hydrogen isotopes have a radioactive nature and nuclear devices have been built and tested containing these materials [12].

Hydrogen has energy per mass content of 143 MJ kg^{-1}, a figure which is up to three times larger than liquid hydrocarbon based fuels [13]. Table 2 [6,7,9,14–17] depicts volumetric and gravimetric energy density of some common fuels.

On the other hand, hydrogen has a very low density in the gaseous state [18] and liquefying such is an energy consuming process. The latter mentioned counts as a drawback for this substance while being used as a fuel. Moreover, hydrogen is not available as a naturally separated material in consumable scale as it is usually bonded with other materials [19], mainly carbon and oxygen.

Table 1
Properties of hydrogen.

Property	Value
Name, symbol, number	Hydrogen, H, 1
Category	Nonmetal
Atomic weight	1.008
Electrons, protons, neutrons	1, 1, 0
Color, odor	Colorless, odorless
Toxicity	None, simple asphyxiant
Phase	Gas
Density	Gas: 0.089 g l^{-1}, liquid: 0.07 g cm^3
Ionization energy	13.5989 eV
Liquid to gas expansion ratio	1:848 (atmospheric conditions)
Melting and boiling point	−259.14 °C, −252.87 °C
Lower heat value (LHV)	118.8 MJ kg^{-1}
Adiabatic flame temperature	2107 °C
Flammability range in air	4–75%
Laminar flame velocity	3.06 m s^{-1}
Flash point	−253 °C
Auto ignition temperature	585 °C
Research octane number (RON)	>130

2.2. Hydrogen versus fossil fuels

According to the published statistics by the International Energy Agency (IEA) currently, the world consumes fossil fuels in very large scales (over 89 million barrels per day). A wide and really enhanced global scientific, social and political infrastructure supports this popularity. This consumption level does not come without problems indeed. Pollutant emission of harmful materials [20–22] and greenhouse gasses [10] accompanied with current global warming issues [23] are only few of their disadvantages. These fuels have limited exhaustive resources [24] and they can be found in certain parts of the planet. Furthermore, political conflict, mainly caused by their highly volatile price [25,26] is a distinct drawback that definitely threatening the existence of the human-race. In addition, these fuels are oil derivatives with a wide range of formulations where each can be fed to a certain and limited group of consumer machinery. These fuels are basically being "burnt" in order to release their energy content, which causes a large fraction of it to release to the atmosphere as heat-waste in the process of combustion [27,28].

Hydrogen, in contrast, has very long-term viability [28]. The resource availability is estimated to have a perspective as long as the existence of the human race [10]. It could be produced by a

Table 2
Volumetric and gravimetric energy densities of common fuels.

Material	Energy per kilogram (MJ kg^{-1})	Energy per liter (MJ l^{-1})
Hydrogen (liquid)	143	10.1
Hydrogen (compressed, 700 bar)	143	5.6
Hydrogen (ambient pressure)	143	0.0107
Methane (ambient pressure)	55.6	0.0378
Natural gas (liquid)	53.6	22.2
Natural gas (compressed, 250 bar)	53.6	9
Natural gas	53.6	0.0364
LPG propane	49.6	25.3
LPG butane	49.1	27.7
Gasoline (petrol)	46.4	34.2
Biodiesel oil	42.2	33
Diesel	45.4	34.6

Table 3
Flashpoint of some common fuels.

Fuel	Flashpoint (°C)
Hydrogen	−231
Methane	−188
Propane	−104
Gasoline	−45
Methanol	11
Ethanol (70%)	17
Kerosene	36
Jet fuel	60
Diesel	62
Biodiesel	130

variety of methods [12,29] virtually anywhere around the globe [16]. This substance could be fed to a wide range of consumers [3,18,19,30] such as turbines, internal combustion engines and fuel cells as well as kitchen ovens and heaters. It should be highlighted that some of the mentioned systems have no moving parts and as a result, desirable mass to energy conversion rates can be obtained. In other words, their efficiency and life span are much higher than those of conventional devices in performing same functions [22]. Micro-scale [31] as well as macro and mega scale [32] production and consumption of hydrogen are realistically feasible. Its consumption comes with minimal harmful emissions [12,18] and the byproduct is only water [12] regardless of the method of utilization. Furthermore, we can add hydrogen to other fuels in order to form energy enriched mixtures [21]. Hydrogen could be used as an alternative fuel for engines designed to run on other fuel forms [21,33–36] where its wide flammability range provides easy controllable engine power [5].

We know that a fuel can be burnt only in the gaseous or vaporized state and hydrogen reaches its gaseous state at very low temperatures. Table 3 [6,7,9,14,17,38,39] shows a comparison between the flashpoint of hydrogen and that of few other common fuels. Flashpoint is known as the temperature at which a fuel generates enough vapor to form a flame at its surface in air [17,37] while an ignition source is present. The flashpoint of a fuel is always less than its boiling point. A fuel flame is very unlikely to last without an ignition source as the vaporization may cease at lower temperatures. As it can be seen in Table 3, hydrogen has the lowest flashpoint in analogy with a wide range of common fuels.

Therefore, hydrogen based engines are expected to require less sophisticated starting and ignition equipment than those which are running on other fuels [18]. Such power sources also can perform normally in conditions that might be counted as "harsh" for other types of engines. As a practical example, hydrogen vehicles are reported to be able to start working after being left in cold temperatures without having ignition for few days. In addition, hydrogen has a unique flammability range. The enormous gap between its lower flammability level (LFL) and its higher flammability level (HFL) [40] caused a wide range of possibilities in order to be consumed as a fuel for combustion engines or turbines [4]. LFL and HFL are the minimum and maximum fuel concentration levels in the air in order to make the mixture flammable. If the fuel content level reaches values below its LFL or over its HFL (refer Table 4), the fuel–air mixture will not be ignitable due to lack of fuel or oxygen in the mixture respectively. The latter mentioned feature shows its importance by knowing that many automotive, transportation and industrial producers have to make enhancements, include additional systems such as turbochargers or in some cases costume design their produced engines in order to be able to perform in low pressure circumstances such as high altitudes. However, hydrogen consumption makes it possible to design and build engines with more structural simplicity in order to perform the same in different situations. Table 4 [5,6,9,40–42] depicts the flammability range of several comparative fuels at ambient pressure and temperature.

Table 4
Flammability range of common comparable fuels.

Fuel	Flammable range (%)
Hydrogen	4–75
Methane	5.3–15
Propane	2.2–9.6
Methanol	6–36.5
Gasoline	1–7.6
Diesel	0.6–5.5

Table 5
Research octane number of comparable fuels.

Fuel	Octane number
Hydrogen	>130
Methane	125
Ethane	108
Propane	105
Octane	100
Gasoline	87
Diesel	30

In addition to the mentioned advantages of hydrogen consumption over fossil based fuels, the octane number of hydrogen should be noted. The octane number states the anti-knock characteristics of a fuel [18]. Knock is the formation phenomenon of a second fuel detonation inside the combustion engine following the main explosion. This detonation occurs because the temperature exceeds the auto ignition level of the fuel. Octane is a measure of anti-knock ability of hydrocarbon fuels and has a rating up to 100. Higher octane levels describe a further ability to prevent unwanted auto ignitions in combustion chambers. However, other types of fuels have also been subjected to tests in order to determine their experimental octane levels [43]. Research octane number of a fuel is the commonest global octane rating method. This number is obtained by running a fuel in a chamber at variable compression conditions. Research octane numbers (RON)s of a few comparable fuels are illustrated in Table 5 [18,44].

2.3. Hydrogen production

A range of methods is in use to generate hydrogen from different resources. Unfortunately, fossil based fuels are still the main recourse for industrial mass scale hydrogen production probably due to their low costs and easy usage in machines that designed for fossil fuels. This fact is absolutely in contradiction with policies towards a green and sustainable energy cycle.

2.3.1. Hydrogen from fossil fuels

Fossil fuels have large and heavy hydro-carbon based molecular structure. Extracting hydrogen by breaking the bonds between hydrogen and carbon content is one of the most popular methods of hydrogen production [16]. This substance can be extracted from biomass [45], coal [46], gasoline, oil (heavy and light), methanol and methane [12].

Nowadays, steam-methane reforming (SMR) is known as the most economical method [19] and has the largest share in global hydrogen production (almost 48%) [47]. The reaction of this highly endothermic process is given by Eq. (1):

$$H_2O + CH_4 \rightarrow CO + 3H_2 \tag{1}$$

Coal and oil have the second and third place in this ranking with 30% and 18% relative share [19]. Hydrogen production by the means of water electrolysis has the smallest share of 4% among the available methods of large scale hydrogen production [48] where other resources are not being used in mass and industrial scales.

Hydrogen is a byproduct of other oil refinement in many cases [12]. Reasonable production price [49] and possibility of mass production [12] are other advantages of fossil fuel based hydrogen production. However, this approach of hydrogen production suffers from problems which are mainly based on their pollution ratings and limited resources. These methods of hydrogen production usually emit CO or CO_2 [12,16] and other greenhouse gasses. The resources are not renewable [16] and the production is not known as "green".

2.3.2. Hydrogen from water

Splitting of water molecule by means of electrolysis has been studied for a long time [50,51]. Water is subjected to an electric current in order to force its molecules to decompose [48]. The occurring half reactions at the electrodes are given by Eqs. (2) and (3).

$$\text{Cathode}: \quad 2H^+ + 2e \rightarrow H_2 \tag{2}$$

$$\text{Anode}: \quad 2OH^- \rightarrow (1/2)O_2 + 2e \tag{3}$$

The overall chemical reaction of a water electrolysis process is given by Eq. (4).

$$H_2O \rightarrow H_2 + (1/2)O_2 \tag{4}$$

As it was mentioned earlier, this method does not have a large share in global hydrogen production. High production costs [52] due to low conversion efficiency and electrical power expenses [3,32,53] can be named as the main drawbacks of electrochemical hydrogen production. Hence, water electrolysis is not a method of choice for large-scale production of this substance, in the present context. As a result, electrolytic hydrogen was not able to find its way as a competitive alternative for traditional fuels.

Water electrolysis process requires a minimum energy of 39.4 kWh kg^{-1} of hydrogen generation at full conversion efficiency. However, typical electrolyzer consumes up to 50 kWh in order to generate 1 kg of hydrogen [54,55]. Many efforts are made in order to increase the efficiency of water electrolysis [52,54,56–58]. Higher efficiencies were obtained in extreme pressure and temperature conditions. At the same time, increased investment is required to build more complex and sophisticated electrolyzers which are able to perform under intense conditions [12]. In these cases, higher production efficiency comes with dramatically increased corrosion, operation and maintenance (O&M) costs and reduced life span [1,52]. On the other hand, estimations show that the monetary investment per production capacity unit reduces as the capacity increases [12]. Therefore, most of the available electrolyzers work at temperatures lower than the boiling point of water and do not exceed the pressure barrier of 50 bar.

Despite the mentioned cost disadvantages, water electrolysis has some unique qualities. Electrolysis could be used for hydrogen production at any place around the globe. The only requirements of this production are electricity and water where the production rate/capacity could be tuned for a certain demand at any place [12,16]. With regard to the characteristics of water electrolysis, this method is capable of producing absolutely sustainable and clean hydrogen. This goal can be achieved if and only if the required electricity is obtained from an emission-free method such as wind, solar, geothermal systems, ocean wave or other renewable and green sources. The latter is further supported by the fact that such energy generating systems can be developed 8 times faster than those with oil-base fuels [28]. Whereas their net energy profile shows very close overall values for both methods over time, there are still some lifespan advantages for the case of renewable approaches.

Every single renewable energy harvesting system has its own capital cost. Utilizing one, all or a combination of few of the new energy production systems is inevitable for future energy production demands [3,16]. However, current concern is to analyze the possibilities of hydrogen production based on the available social, industrial and political infrastructures. Schoots et al. [49] calculated the required investment cost as 1000 US$ kWh^{-1} for nominal power of the hydrogen production plant. Referring to the mentioned power demand of hydrogen generation, the estimation is that a plant requires an investment of 50,000 US$ for each 1 kg h^{-1} capacity of electrolytic hydrogen production. *On the other hand, evaluations show remarkable reductions of expense as the production capacity increases* [12].

Table 6
Auto ignition temperature of comparable fuels.

Fuel	Auto ignition temperature (°C)
Hydrogen	585
Methane	540
Propane	490
Butane	405
Methanol	358
Gasoline	246–280
Diesel	210

2.4. Hydrogen safety

Hydrogen is not toxic, yet extremely flammable [16,19,30]. Its laminar burning, buoyant and propagation velocities are significantly higher than those of other fuels [12,36]. Meanwhile, its flame temperature at the presence of ambient oxygen content is almost the same as that of the others. However, its vapor-from-liquid-generation-speed is much higher than that of any fossil based liquid or liquefied fuel. The mentioned properties cause a hydrogen fire to last 0.1–0.2 time of a hydrocarbon-consuming fire with the same volume of fuel [12]. Unlike any other fires, smoke inhalation of hydrogen fire is absolutely harmless. Therefore, chocking-hazard rates of hydrogen fires are expected to be minimal since smoke asphyxiation has the largest damage-share among hazards of fires [37,59].

Hydrogen is a material with high sensitivity to detonation [46]. As it was mentioned earlier, its wide oxygen mixture range of ignition and detonation [18] clarifies how delicate its storage is.

One of the most important safety issues in accordance with handling a fuel is its auto-ignition temperature. This term expresses a temperature at which a material will ignite without any external ignition sources. It is known that the auto-ignition temperature is related negatively to the pressure or oxygen concentration of the surrounding environment. However, according to the flammability range of hydrogen, its auto ignition temperature is expected to be unaltered at higher pressures or oxygen concentrations. On the other hand, hydrogen has the highest auto-ignition temperature among other fuels. Table 6 [6,7,15,18,55] shows the auto ignition temperatures of a few comparable common fuels.

As it can be seen in Table 6, hydrogen has a very desirable auto-ignition temperature which is a positive safety aspect of fuels. On the other hand, the very low electro-conductivity rating of hydrogen might be a concern as its agitation or flow in both liquid and gas states generate electrostatic charges which are able to trigger sparks. Therefore, all equipments in direct contact with hydrogen should be electrically grounded.

Hydrogen has been produced and handled for several decades and the technology and regulations of safe storage and transportation of this substance are available. With regard to all stated points, hydrogen storage and consumption does not have any significant additional risks compared with other liquid or gas fuels [12,16]. It is the common agreement among many scientists that hydrogen is much safer than other fuels in wide usage at present [5].

2.5. Hydrogen storage

As it is mentioned before, uncompressed gas state hydrogen has a very low density and energy content. In other words, wide use of this material as a fuel has some technical problems. There are several storage techniques used for hydrogen out of which the most conventional is to store it as a compressed gas in tanks [60]. High pressure levels are preferred in this regard. However, construction constraints, cost of production and maintenance and operational safety of the tanks and compressors limit the extent to which the gas can be pressurized.

As it is mentioned in Table 2, hydrogen has much higher energy content in liquid form than in the compressed gas state [60,61]. The main advantage of storage of liquefied hydrogen is its high density in low pressure. These features enable compact and light weight storage and efficient delivery options [3,19,62]. Hydrogen liquefies at temperatures below $-250\,^{\circ}\mathrm{C}$ and that is why the liquefying process of hydrogen adds an excess 30% to the production power demand. Furthermore, utilizing gas liquefiers add more sophistication to the production system. As a result, liquid hydrogen costs 4–5 times more than the compressed gas state product [12].

Storing hydrogen in high pressure vessels is currently the method of choice for most of the vehicle manufacturers due to the efficiency, design, cost and environmental advantages [63]. Gas compression is known as the most time and energy efficient method which is able to provide an easy to use source for consumers. Low storage density counts as the main disadvantage of this approach. Hence, many professionals anticipate that hydrogen storage in high pressure cylinders is very unlikely to be a popular method in future [64].

Hydrogen can also be stored in materials with high storage-capacity in different forms of metal hydrides [61,65], Mg-based alloys [66–69], a few carbon-based materials [70,71], chemical hydrides [72] and boron compounds [73]. Some metals are able to build a chemical bond with hydrogen as per their interatomic lattice [12,74]. In this method, hydrogen is bonded to the metal in reduced temperatures and releases the gas by getting heated. An advantage of this method is the ability of bonding at normal or low pressures and releasing at high pressure conditions [12]. The most novel method of this sort is called the “chemical hydride slurry approach” [61,72,75]. In this method, the reaction between hydrogen and a chemical hydride/organic slurry is used in order to store hydrogen. The high purity hydrogen can be extracted at the point of use from the media by the reaction between the slurry and water. The hydride/organic sculleries usually have a fluid-like nature which brings unique opportunities of storage, transportation and pumping. Improvements in energy transmission of hydrogen, stabilizing the stored fuel at normal temperature and pressure, high volumetric energy content and very low harmful emissions could be named as the advantages of this method. Calcium, lithium, magnesium and sodium have the most usage in this approach.

It should also be noted that materials with constant and direct contact with hydrogen become brittle. This phenomenon is known as hydrogen embrittlement [76,77] which can affect a variety of metals, even high-strength steel [78]. This phenomenon starts with the diffusion of lone hydrogen atoms through the metal. Small amounts of hydrogen can diffuse into the metal at high temperatures whereas concentration gradient assists the diffusion at low temperatures. While re-combining in minuscule voids of the metal in order to form hydrogen molecules, these atoms create pressure from the cavity they are trapped in. This pressure may increase to the point that causes the metal to crack open. On the other hand, the fact should be noted that guidelines are developed in order to prevent the mentioned safety issues. By adhering to the recommended safety, overhaul and maintenance procedures, undesired safety issues and consequential damage and losses can be prevented.

2.6. Global perspective

2.6.1. Production cost reduction

Electrolytic hydrogen production from renewable energy sources is of a great benefit. We know solar farms and photovoltaic cells are able to generate electricity during the daytime while power demand is not at its peak period. This problem is usually counted among the main drawbacks of solar energy harvesting. In addition, we know that the output of nuclear power plants cannot be altered fast enough to meet the exact load demand. Hence, a portion of the generated power is wasted during the off-peak times, although such plants are usually being utilized to meet the baseline of load power demand. Likewise, in the case of more conventional power production such as diesel, natural gas or combined-cycle power plants, dummy loads required to consume the excess production to maintain the stability of the system.

For an example, it is reported that in a particular wind farm in northwestern Spain, a sizable section of the farm has to be disconnected regularly from the power grid in order to maintain stability during the off-peak hours [79]. Operators stated a total annual waste of 13 GWh of electrical energy due to this off-operation. This energy can easily be utilized to produce enough hydrogen to fuel a fleet of 728,000 cars if each requires an amount of 2.5 kg of hydrogen per refueling per week for one year. This calculation was based on the assumption of a weekly journey of 400 km for each vehicle for a year. As it is noted in Table 7, such vehicles are currently available in the market.

The mentioned points are only a few examples that emphasize the undesired power wastage only at the production level, which can be utilized to generate hydrogen. Electricity tariffs published by power suppliers worldwide show a normal rate of around 40% discount in electricity price in developed countries. Much higher price reduction rates are also reported in certain regions. As electricity price covers the major part of hydrogen production costs, the expense of fuel generation can be reduced at least by the same mentioned factors. By considering all the on-site plant power waste, further drop of the total electricity price is expected during certain times of the day.

Botterud et al. [80] evaluated the relation between the costs of electricity and electrolytic hydrogen generation. Their research covers costs of two different methods of high pressure electrolysis-advance light water reactor (HPE-ALWR) and high temperature electrolysis-high temperature-gas cooled reactor (THE-HTGR). Both mentioned approaches show promising efficiency levels among the available methods.

In addition, electricity tariff of an energy provider company [81] from the same economic region of the mentioned study shows a total amount of 0.11677 US$ kWh^{-1} during the peak and 0.05077 US$ kWh^{-1} during the off-peak hours for commercial and industrial services for up to 200 kW. Moreover, the average price per kilogram of hydrogen at the time of writing of this paper is pronounced around 5 US$ kg^{-1} at fuel stations over the United States of America. Referring to Fig. 1 [80], utilizing off-peak electricity for local hydrogen production can reduce its production price down to around 2.5 US$ kg^{-1} while the production price with peak period power is absolutely outperformed by current methods. We should notice that published literature shows much less off-peak electrical power price in some places. For example, the off-peak price of nuclear-based electricity is expressed to be as low as 0.03 US$ kWh^{-1} [82]. Availability of electrical power in this price range makes it possible to mass produce hydrogen as cheap as 1.5 US$ kg^{-1}.

Table 7
Fuel cost comparing between a few hydrogen and gasoline based vehicles.

Manufacturer	Model	Range with hydrogen fuel (km)	Gasoline consumption (l/100 km)[a]	Hydrogen storage capacity (kg)	Cost of a 100 km journey on gasoline (US$)	Cost of a 100 km journey on hydrogen (US$)	Estimated cost of a 100 km journey with locally produced hydrogen (US$)[b]
BMW	Hydrogen 7 (V12 6.0l ICE)	201	13.9	8	13.43	19.90	13.93
Audi	A2H2	220	5	1.8	4.83	4.09	2.86
Toyota	FCHV bus	690	–[c]	6	–	4.35	3.04
Volkswagen	Touran HyMotion 2004	160	7.2	1.9	6.96	5.94	4.16
Volkswagen	Touran HyMotion 2007	230	6.5	3.2	6.28	6.96	4.87
GM	Hydrogen Minivan	270	–	3.1	–	5.74	4.02
GM	H2H Hummer (V8 ICE)	100	17	5.5	16.42	27.49	19.25
KIA	Borrego FCEV	690	13	7.9	12.56	5.72	4.01
KIA	Sportage	400	8	3.5	7.73	4.37	3.06
Honda	FCX Clarity	430	–	2.7	–	3.14	2.20
Mitsubishi	Lancer Evo IX Hydrogen (Wankel Engine)	110	8.7	2.2	8.40	10.00	7.00
Peugeot	207 Epure (ICE and FC)	350	6.6	3	6.38	4.28	3.00
Mazda	Premacy Hydrogen RE Hybrid	200	11	2.4	10.63	6.00	4.20
Daimler Mercedes-Benz	B-Class F-Cell	400	6	11.1	5.80	13.87	9.71
Mercedes-Benz	F125 Concept	1000	–	7.5	–	3.75	2.62
Hyundai	Tucson FCEV	650	7.5	5.6	7.25	4.31	3.01

ICE, internal combustion engine; FC, fuel cell; FCEV, fuel cell electric vehicle.
[a] Based on the same models with gasoline engines or the same vehicles with hybrid fuel consumption.
[b] Based on a 30% reduction in the costs of production.
[c] No gasoline model has been produced.

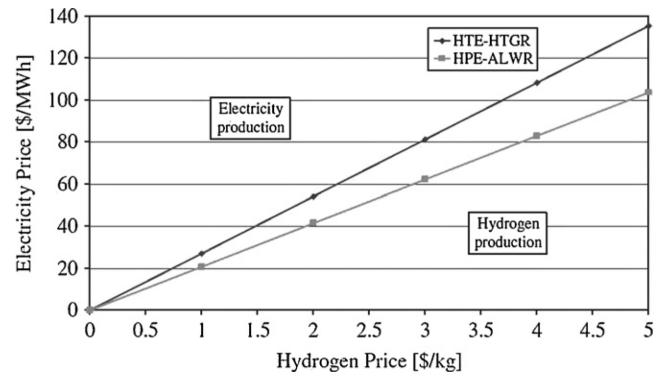

Fig. 1. Hydrogen price versus electricity price.

2.6.2. Distributed production

Regarding the benefits of localized hydrogen production, this method seems to be a proper approach in the process of substituting fossil based fuels with hydrogen. In this method, the energy production surplus could be franchised to consumers within any distance from the power sources such as refueling stations, industries and even a part of the residential section which are willing to produce and store their own transportation fuel. A conventional IP-based networking can be utilized for transmission of the required data such as momentary demand and available power as well as issuing the start/stop commands to the consumers. In this way, local hydrogen producers are able to be engaged/dis-engaged right at the time of availability/unavailability of excess power. As an electrochemical process, electrolytic hydrogen production can be started/stopped fast enough to meet the stability control requirements of power plants and power grids. The latter means that local hydrogen production devices are able to function as dummy loads for power plants.

This method does not demand any infrastructural investment since the available electrical power distribution grids are expected to be able to handle the required power transmission during the off-peak periods. As mentioned in the prior sections and also illustrated in Fig. 2 [12], the investment costs of hydrogen production plants have inverse correlation with the size of the plant. However, substitution of large-scale electrolyzers with smaller ones is still a practical solution hydrogen production at a reasonable price. Mass-production of small scale electrolyzers, their parts, compressors and storage tanks will lead to obtaining a cheap, yet effective method of water electrolysis for hydrogen mass-production.

2.6.3. Expansion possibilities

High production cost is always named as one of the most critical drawbacks of utilizing hydrogen fuel. Table 7 compares the price

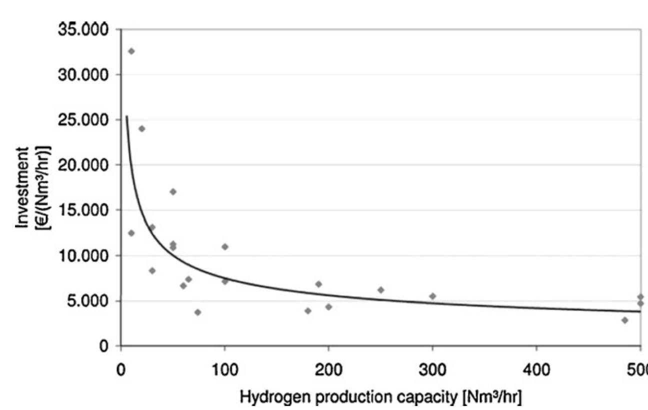

Fig. 2. Investment costs for alkaline electrolyzers.

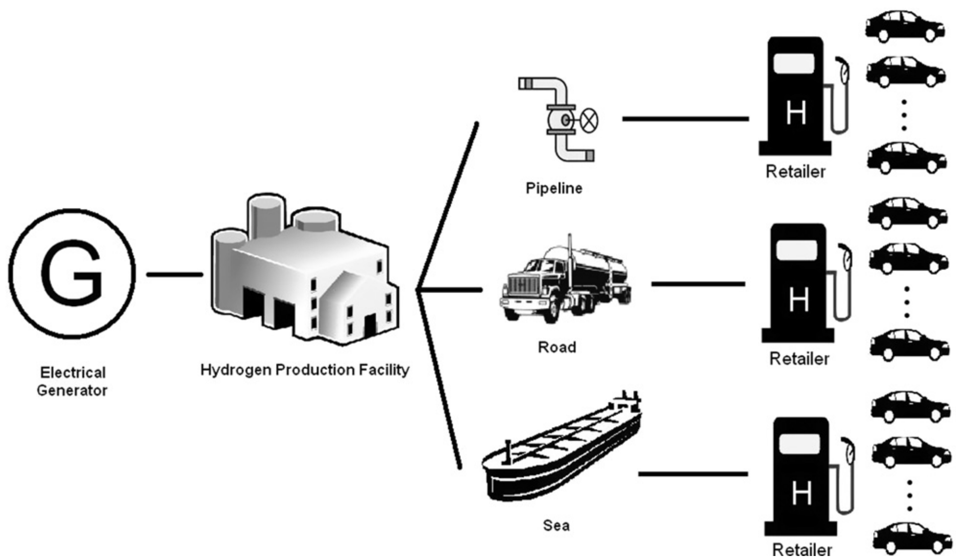

Fig. 3. Large scale hydrogen production and distribution.

of a 100 km journey for a number of vehicles. Gasoline and hydrogen fuel prices are extracted from the monthly average prices in the United States for September 2011 as 3.535 $ per US-gallon and 4.999 per kg respectively [83,84].

Table 7 clarifies that, vehicles with internal combustion engines are absolutely outperformed by those powered by fuel cells. However, utilizing hydrogen fuel for combustion engines and fuel cells are forecasted to be of almost the same efficiency in future. Nevertheless, there will still be some advantages in using fuel cells [18].

The values in the last column of Table 7 are calculated by assuming a reduction of 30% in electricity cost which is based on the average of discounts on electricity tariffs. The numbers in this column are only meant to give an idea about the economic advantages of distributed small scale hydrogen production. Authors believe that the total costs of utilizing hydrogen in transportation can be even less than the stated values. Complete elimination of fuel transportation and utilization of surplus energy (produced and wasted) are critical to achieve this goal.

2.7. The size of production units

There are different possibilities for electrolytic hydrogen production in order to meet the consumer demands. One is to perform the electrolysis in gigantic plants and transmit the fuel to distribution outlets such as fuel stations. As another approach, it is possible to equip the refueling outlets with water electrolysis and gas compressor/liquefier systems to generate the fuel on-site. The third option is to produce hydrogen in household refueling systems. In this case, each end user is provided with an electrolyzer, a compressor/liquefier and a refueling device. Advantages and disadvantages of these methods are analyzed in the following sections.

2.7.1. Large scale production

Producing massive amounts of hydrogen in a single plant comes with highly reduced monetary capital investments per unit of product. As it is illustrated in Fig. 2, assessments show noticeable capital cost reductions as the production capacity increases. However, the graph does not have a constant slope. Hence, it seems to be more economically efficient to build mega-Watt scale hydrogen production facilities although total investment cost per production unit is not going to change much after certain capacity barriers. Another advantage of this approach is the plant concentration which makes it easier to manage, troubleshoot and service. In this case, the number of required human resources is expected to be less than the other methods. Fig. 3 shows the basic structure of this method.

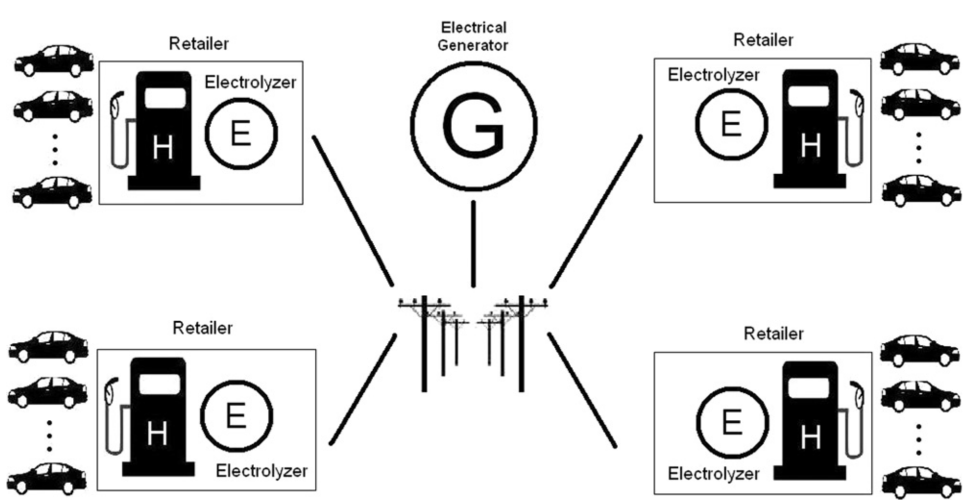

Fig. 4. Localized medium scale hydrogen production.

Table 8
Major hydrogen transmission methods.

	Tube trailer	Liquid via road	Pipeline	Liquid via ships
Suitability	Short distance gas state transfer	Short and medium distance transfer of large volumes of fuel	Short, medium and large distance transfer of large and very large quantities in gas state	Very large quantities of gas for international transportation
Investment Costs	Around 300,000 $ per truck plus	Up to 400,000 $ per truck	200,000–1,000,000 $ per 100 km depending on the terrain	1,55,000,000 $ for gas and up to 7,00,000,000 $ for liquid barges
Operating and Maintenance costs	Driver labour at around 18 $/h	Driver labour at around 18 $/h	Around 0.03 $ per kg for pipeline compressors	Uncertain amount for crew labour and fuel consumption
Efficiency	94% per 100 km	99% per 100 km (liquefaction efficiency is around 75%)	Over 99% per 100 km	Unknown fuel use and 0.3% boil-off
Capacity	Up to 400 kg per truck	Up to 4000 kg per truck	Up to 100 tons/h	Up to 10,000 tons per shipment
Energy consumption	Vehicle fuel consumption	Vehicle fuel and liquefaction energy consumption	Electricity requirements for pipeline compressors	Transport fuel
Advantages	Small scale deployment possibilities	Larger volumes than gas transportation	Large and very large quantities can be transported to any distance with high efficiency, low running costs and very low variable expenses. This method also provides storage and buffering possibilities	International transportation of massive quantities for long distances
Disadvantages	Small scale delivery per vehicle, energy inefficiency, short distance transportation	Costs and inefficiency of liquefaction and boil-off product losses	Relative expensive investment costs, requirement of very large amount of hydrogen to be justified.	There is no experience available for liquid hydrogen transfer. Cannot be justified unless large production and demand are available. More boil-off losses than other methods
Maximum estimated transmission cost US$/kg/100 km	2.00	0.5	1.00	2.00

On the other hand, building large scale fuel production plant has its own disadvantages as well. Balat [19] reported the cost of hydrogen storage tanks to rise drastically for larger capacities. Their research indicates an industrial 50 kg hydrogen tank costs slightly more than 50,000 US$ while a 150 kg tank will cost around 300,000 US$. They used their database to develop correlation which shows price increment of almost 100,000 US$ per each 50 kg extra storing capacity.

This method also has to overcome the challenge of product transmission. Four major fuel shipping possibilities have been analyzed in order to assess their capacity, efficiency and transmission costs. Table 8 [19] shows the characteristics, advantages and disadvantages of these methods.

2.7.2. Production at sales outlets

Hydrogen can be produced in small scales at places such as refueling stations. Utilizing this method of fuel production eliminates some of the disadvantages of large scale hydrogen generation.

As it was mentioned earlier, the cost of building large scale hydrogen tanks will become unreasonably high for huge storage capacities. Published statistical data by U.S. Census Bureau [83] and Research and Innovative Technology Administration, a branch of Bureau of Transportation Statistics [84] show a rate of roughly 200 cars attending to a normal fuel station in the United States daily. Assuming a requirement of 2.5 kg of hydrogen per vehicle, each station has to provide 500 kg hydrogen every day. In addition, US Department of Energy [85] expresses a period of 6 h of peak

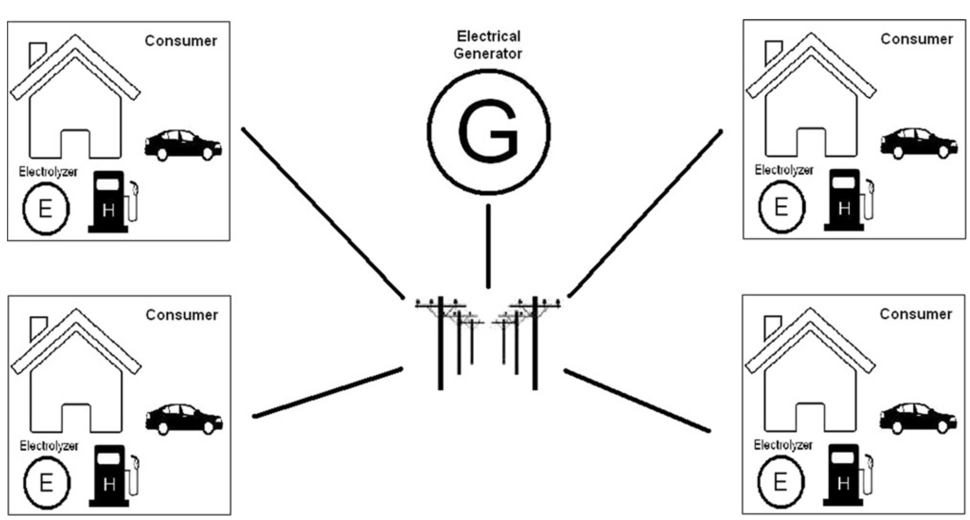

Fig. 5. Small scale distributed hydrogen production.

and 18 h of off-peak time during the weekdays. Hence, by assuming the mentioned amount of hydrogen to be generated during the whole 18 h period, a tank with the maximum capacity of 1/4 size of the daily supply will be sufficient for each station. In this case, the investment cost of building storage tanks will be minimal.

Moreover, none of the expressed transportation costs are applicable for this approach since each production site is provided with the required electricity supply, which can be used for gas generation. The latter will reduce up to 2 US$/kg hydrogen, depending on the means of fuel transportation.

Since most of the vehicles rely on gasoline based engines, the development of hydrogen vehicles can be started without multi-billion dollar investments. Current fuel stations can be equipped with hydrogen fuel dispensers to satisfy the needs of local markets. Number of outlets and equipment per outlet can be increased gradually. Meanwhile, vehicle manufacturers will face new opportunities to enhance their designs and improve the number of their hydrogen based productions. In this approach, both providers of vehicles and fuel will gain public trust on a hydrogen based transportation economy. The concept of hydrogen production at the distribution points is illustrated in Fig. 4.

2.7.3. Household scale production

During the last few years, several major companies introduced home-level hydrogen stations. Their earlier models generated hydrogen from natural gases while the most recent systems use solar energy to produce this fuel by means of water electrolysis. The mentioned refueling systems are still under experiment, mainly in the United States [86]. The consumer price of this system is not officially stated, and it is not available for public to purchase. We believe equipping each hydrogen vehicle owner with one mini fuel station might be a short-term solution to overcome the unavailability of public facilities. However, this solution does not seem to be able to outperform the previous method, especially when macro-economics is the subject of debate.

Fig. 5 is a schematic showing the structure of small scale hydrogen production.

3. Conclusions

This study provides solid information on the feasibility of developing the industry of producing hydrogen as a fuel or energy carrier, at several scales. Based on our analysis would like to make the following recommendations.The following advantages of hydrogen as a material over other competing fuels should be fully exploited

1. Possibility of mission free consumption.
   a. Higher gravimetric energy content.
   b. Possibility of feeding systems which are designed to utilize other fuels.
   c. Requirement of less complex energy harvesting machinery and equipment.
   d. Possibility of fuel production localization.
   e. Possibility of production from renewable energy sources.
   f. Unlimited resources.
2. The following drawbacks of hydrogen as a materials should be taken into account and addressed adequately when it is used as a fuel or energy career
   a. Low volumetric energy content.
   b. Requirement of developing country-scale infrastructures in order to be counted as a substitute for fossil-based fuels.
   c. High transportation costs.
3. It is highly profitable to produce hydrogen by utilizing the surplus energy wasted in dummy loads (to maintain the system stability) in large scale grid systems (at generation end).
4. Power produced in distributed generators based on alternative energy sources can also be used for the generation of hydrogen, especially during off-peak hours.
5. In large grids, at consumer level it is profitable to produce hydrogen by electricity during off peak hours. This can be done at large consumer level (at gasoline stations) or retail consumer level (homes and small scale installations).
6. Storage of hydrogen is less costly when small to medium sized containers are used. As the capacity of the container exceeds medium scales, the cost of storage becomes excessively high.
7. Risk of handling hydrogen is equal or less than that of other competitive fuels. However it is emphasized to develop universal safety guidelines for mass handling of hydrogen as it becomes a day-to-day fuel.
8. Initially, it is proposed to use energy through hydrogen in gasoline-based engines themselves due to the practical constraints. As the usage increases 100% hydrogen fuel based automobiles and stationary engines can be constructed.

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